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Characterization of neutron irradiated, low-resistivity silicon detectors

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Abstract

A complete electrical characterization of silicon detectors fabricated using low- ($\simeq 1.5 \text{ k}\Omega \text{ cm}$) and high- ($> 5 \text{ k}\Omega \text{ cm}$) resistivity substrates has been carried out. Measurements have been performed before and after neutron irradiation at several different fluences, up to $3 \times 10^{14} \text{ n cm}^{-2}$ (1 MeV eq.).

Experimental results have been compared with CAD based simulations. A good agreement has been found, thus validating the CAD model predictions.

The adoption of low resistivity devices appears to have some definite advantages in terms of depletion voltage, which in turn results in better interstrip capacitance and interstrip resistance.

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1 Introduction

Silicon microstrip detectors play a fundamental role in the tracking systems of high energy physics experiments. Due to the harsh radiation environment in which they will operate in the experiments foreseen at the Large Hadron Collider (LHC) at CERN, radiation-hardness represents a key issue for the design of such devices. In the last few years a great effort has been devoted to improve the radiation hardness of silicon detectors, in order to obtain sensors that could survive for the whole duration of the LHC experiments (ten years). The most critical aspect is the increase of the depletion voltages in heavily irradiated detectors. This implies an increase in the detector operating voltage, resulting in a higher breakdown risk. In this frame, relatively-low resistivity silicon was proposed for building radiation-harder detectors. The reason of this choice is to increase the inversion fluence ϕ_{inv} (defined as the fluence at which an n -type silicon becomes “effectively” p -type) in order to have a lower depletion voltage for higher fluences. This concept can be expressed by the empirical formula:

$$\phi_{inv} \approx (17 \div 20)N_{eff},$$

where ϕ_{inv} is expressed in cm^{-2} and the effective doping concentration, N_{eff} , in cm^{-3} . Lower resistivity means higher doping concentrations, thus resulting in radiation-harder detectors. The lower limit on resistivity is set by the depletion voltage before irradiation, which is inversely correlated to the initial resistivity.

A confirmation of these theoretical suppositions was given both by results on small diodes [1] and by computer simulations [2].

In particular, in order to predict devices performance before their actual fabrication, the general-purpose device simulator HFIELDS, suitably modified to account for radiation-related effects [2], has been exploited. Different DC- and AC-analyses have been carried out, aiming at evaluating the main parameters of irradiated detectors (e.g. leakage current, substrate capacitance and depletion voltage).

The damage effect was modelled at a physical level accounting for “deep-level” radiation-induced recombination centers, described by means of a generalized Shockley-Read-Hall statistics [2]. In particular, according to the main experimental findings [3], two deep levels were considered, the dominant “acceptor” level being related to the divacancy VV(-/0) complex, and the dominant “donor” level to the C_iO_i complex. The main parameters of such defects, as adopted in the numerical model, are summarized in table 1. Here, σ_n and σ_p represent the capture cross-sections for electrons and holes, respectively.

	Acceptor	Donor
E	$E_C - 0.42 \text{ eV}$	$E_V + 0.36 \text{ eV}$
σ_n	10^{-16} cm^2	10^{-15} cm^2
σ_p	10^{-15} cm^2	10^{-16} cm^2

Table 1: *Deep-level trap parameters.*

The depletion voltage of progressively irradiated devices has been calculated and related to the radiation fluence: as illustrated in fig. 1, a beneficial effect in terms of reduction of the depletion voltage can be obtained in the medium-long term of the detector operations with the adoption of relatively-low resistivity substrates. According with these preliminary results, as well as with previously related work (e.g. [2], and works therein referenced), a complete experimental characterization of low resistivity detectors has been carried out.

In this work we present and compare some results of an extensive irradiation program (up to fluences higher than those expected after ten years of LHC) performed on silicon microstrip detectors fabricated using low resistivity (LR, $\simeq 1.5 \text{ k}\Omega \text{ cm}$) and high resistivity (HR, $> 5 \text{ k}\Omega \text{ cm}$) substrates.

2 Irradiation conditions

In order to compare the radiation hardness of LR and HR substrates, some care has been exercised to ensure that LR and HR samples undergo the same fluence. Each substrate contains a “baby” (128 strips, 3 cm long) microstrip detector, one diode and other test structures. LR and HR substrate pairs were then closely packed together and irradiated at the nuclear reactor “Tapiro” in the ENEA-Casaccia laboratory (Rome, Italy). The flux of this reactor has recently been recalibrated [4] to an equivalent flux of 1 MeV neutrons. Ten LR and ten HR substrates were irradiated in the “thermal column” of the reactor at a temperature of about 20 °C and unbiased. The irradiation was performed in five steps reaching an 1 MeV equivalent nominal fluence of: $\phi_1 = 0.3 \times 10^{14} \text{ n cm}^{-2}$, $\phi_2 = 1.0 \times 10^{14} \text{ n cm}^{-2}$, $\phi_3 = 1.7 \times 10^{14} \text{ n cm}^{-2}$, $\phi_4 = 2.4 \times 10^{14} \text{ n cm}^{-2}$, $\phi_5 = 3.1 \times 10^{14} \text{ n cm}^{-2}$. The estimated errors on

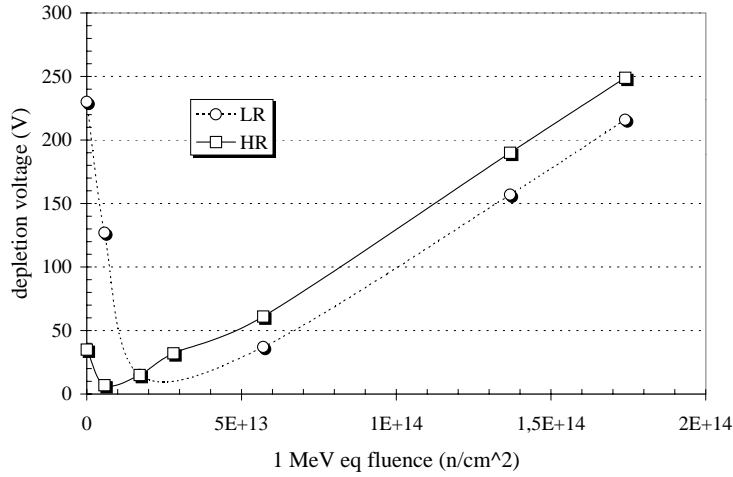


Figure 1: Simulated depletion voltage vs fluence for LR and HR diodes.

those fluences is 20% [5]. After each irradiation step two couples of substrates were removed and kept at low temperature, so that at the end of the irradiation we had two LR and two HR samples irradiated for each of the five fluences.

3 Experimental results

Electrical measurements were carried out in a laboratory under controlled atmosphere and temperature ($\sim 20^\circ\text{C}$). Current measurement were performed by means of a Source Measure Unit Keithley 237. The expected increase in volume current due to irradiation is parametrized by the well known formula:

$$\frac{\Delta I}{\mathcal{V}} = \alpha \phi,$$

where ΔI is the bulk current increase due to irradiation, \mathcal{V} is the active volume of the detector, and α is an empirical constant called “damage constant”. The experimental value of α varies in the range $5 \div 10 \times 10^{-17} \text{ A cm}^{-1}$ soon after irradiation and decreases to $\sim 3 \times 10^{-17} \text{ A cm}^{-1}$ after few weeks of annealing at room temperature [6]. The α values extracted from the diodes currents are reported in table 2, while the fig. 2 shows the total current measured on detectors after the irradiation at ϕ_3 (the expected fluence after ten years of operations at LHC). We extracted the α values from diodes because the active volume is better defined than for microstrip detectors. As mentioned before these measurements were affected by the error on the fluence; moreover, in our experimental set-up we were not able to distinguish the contribution of the surface current, gathered by the guard ring, from the total current and this might result in an overestimate of the α parameter. Previous simulation work [2] had pointed out that no difference would have been expected in the leakage current of LR and HR detectors once the full depletion voltage had been reached. Our results on diode currents show a slightly smaller α for the LR substrate, and roughly the same $I - V$ characteristics for the detectors.

	soon after	after 2 weeks
Low resistivity	$\sim 8 \times 10^{-17} \text{ A cm}^{-1}$	$\sim 5.4 \times 10^{-17} \text{ A cm}^{-1}$
High resistivity	$\sim 10 \times 10^{-17} \text{ A cm}^{-1}$	$\sim 6.7 \times 10^{-17} \text{ A cm}^{-1}$

Table 2: The damage constant measured on LR and HR diodes, soon after irradiation and after two weeks annealing at room temperature

The main difference we expected using LR detectors was a gain in the depletion voltage after type inversion. Fig. 3 shows the depletion voltages measured on diodes as a function of fluence. The values were extracted from $C - V$

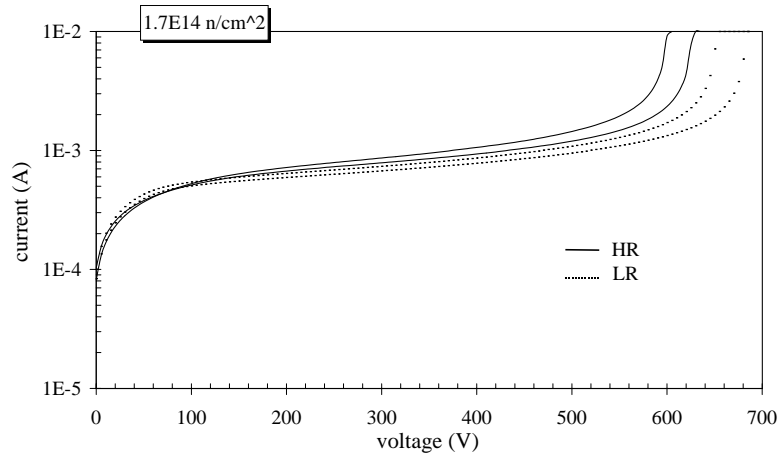


Figure 2: Total current vs bias voltage for LR and HR detectors irradiated at ϕ_3

measurement from the “knee” of the $1/C^2$ vs V curve. Capacitance measurements were performed at a frequency of 100 kHz using a Keithley 590 capacimeter, while the diode was biased by means of a Keithley 237.

A first set of measures has been carried out just after the irradiation and, later, after a 15-days annealing period. A comparison of the various curves for LR and HR diodes show that once the LR substrate had reached type inversion, the depletion voltage is about 100 V higher for HR samples than for LR ones. The “gap” in depletion voltage is approximately constant beyond the LR inversion fluence, and seems not to be affected by the annealing process.

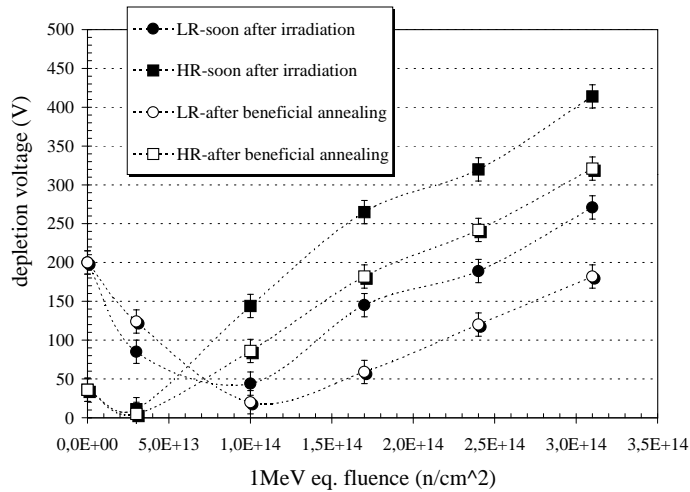


Figure 3: Depletion voltage vs fluence for LR and HR diodes, measured soon after irradiation and after the beneficial annealing.

The lower depletion voltage measured on LR substrates should be accompanied by a better performance of other detector characteristics in order to achieve a higher radiation resistance. In particular, interstrip resistance and

interstrip capacitance in an inverted detector reach their plateau value at voltages higher than full depletion. Fig. 4 shows the interstrip resistance as a function of the bias voltage measured on detectors irradiated at ϕ_3 ; curves for other fluences are similar. The interstrip resistance measured before irradiation was well above 10 G Ω . This value is greatly degraded by irradiation; it is already reduced to few hundreds M Ω at ϕ_1 and decreases down to tens M Ω at higher fluences. Nevertheless this value is still acceptable if, as required, the polysilicon bias resistors are in the range of few M Ω . The curves show that the plateau value is reached at a lower voltage in the case of LR detectors. This is a direct consequence of the different depletion voltage, since, for an inverted detector, the isolation between strips increases once the substrate is fully depleted.

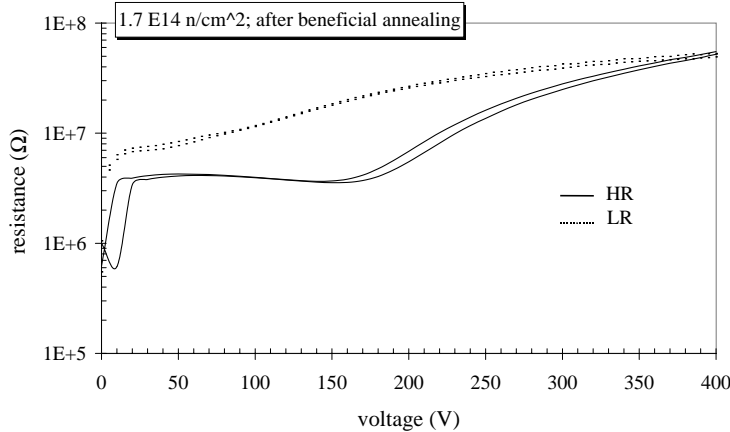


Figure 4: *Interstrip resistance vs bias voltage for LR and HR detectors irradiated at ϕ_3*

The interstrip capacitance as a function of bias voltage is shown in fig. 5 in the case of samples irradiated at ϕ_3 . Before irradiation the value reached at full depletion by LR and HR detectors is the same. Due to irradiation, positive charges are trapped in silicon dioxide at the interface with silicon, resulting in an increase of interstrip capacitance. Moreover, if the detector is inverted (as in the case of fig. 5) and the junction has moved from the front to the back side, the interstrip capacitance measured before full depletion is still higher. Nevertheless it is necessary to substantially overdeplete the substrate to increase the electric field on the front in order to fully deplete the region between strips and recover the pre-irradiation interstrip capacitance value. This is shown by the behaviour of the curves plotted in fig. 5. Having a lower depletion voltage results, at a fixed operating bias voltage, in a lower interstrip capacitance, which is, in turn, the case of LR vs HR irradiated detectors.

4 Conclusions

In this paper, detectors fabricated using both relatively LR (~ 1.5 k Ω cm) and HR (> 5 k Ω cm) substrates have been characterized and compared. In order to test their radiation hardness, we performed an irradiation program using detectors featuring the same geometry. We irradiated the detectors with neutrons at various fluences up to 3.1×10^{14} n cm^{-2} (higher than the one expected after ten years in CMS for the most irradiated detectors). As expected, the HR substrate reaches type inversion at a fluence lower than the LR. Therefore, at high fluences the depletion voltage is lower for LR than for HR. The lower depletion voltage involves other improvements in the detector parameters. Higher interstrip resistance and lower interstrip capacitance were measured on LR detectors at a fixed bias voltage. This, in turn, should result in better performances. A detailed test beam program is under way as well, to study charge collection efficiency, detection efficiency, space resolution, etc. Similarly, one could obtain the same performances from HR detectors, but at a higher operating voltage, which substantially increases breakdown risk.

Although LR sensors feature a higher depletion voltage before irradiation and for the first few years of operation at CMS, this is not a problem for detectors which are not damaged by radiation and have fulfilled the severe criteria

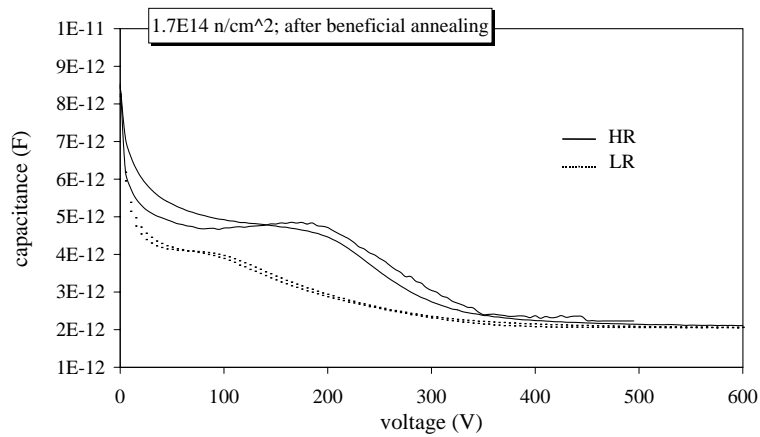


Figure 5: *Interstrip capacitance vs bias voltage for LR and HR detectors irradiated at ϕ_3*

for acceptance. On the other hand, our measurements showed no disadvantage from the point of view of leakage current or breakdown risk in using LR substrates. In short, LR detectors show definitive advantages for the hard environment of the inner tracker of CMS.

References

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